

Deadline-Aware Transmission Scheduling for Satellite IoT Networks

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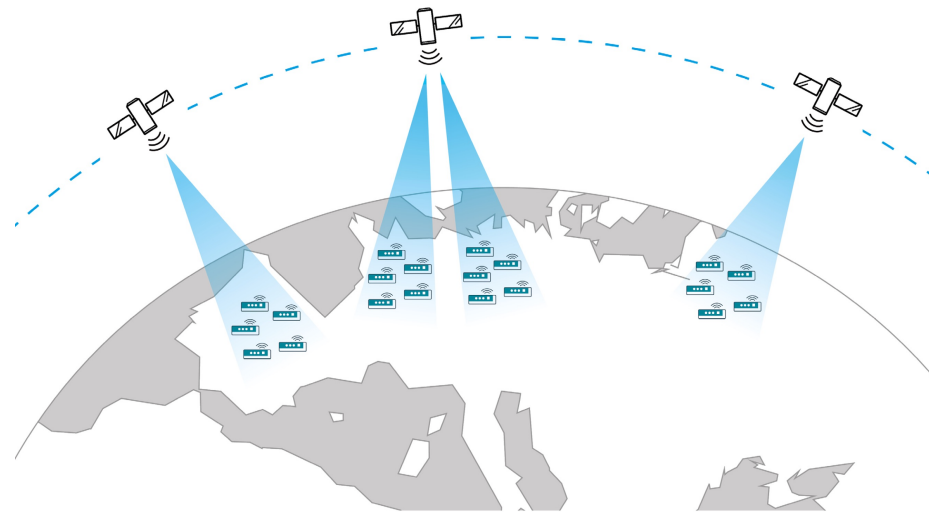
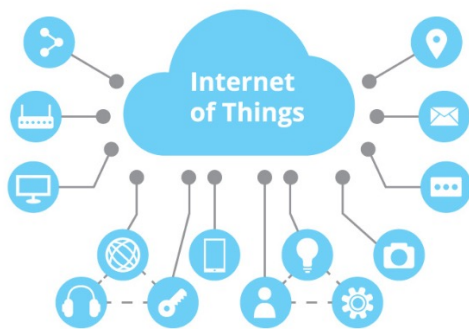


IoT Data Collection over LEO Networks

IoT devices are widely deployed for monitoring and sensing

LTE/5G fails to support full coverage

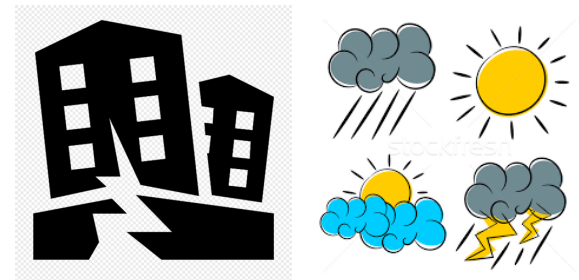
Low-Earth-Orbit (LEO) satellite constellations provide global coverage



Deadline of IoT Data Collection

IoT data are time-sensitive with **varying deadlines**

- Data with short deadline need to be forwarded on time
- Data with long deadline can be cached temporarily



Schedule data transmissions based on **heterogeneous deadlines**

Related Work

Deadline-oblivious traffic scheduling

- Downlink Scheduling [1-2]
 - Uplink scheduling [3-5]
- Maximizing throughput or minimizing latency

Priority-aware traffic scheduling

- Prioritization based on Age-of-Information (AoI) [5-6]
 - UAV trajectory planning for dynamic networks [7-8]
- Do not explicitly guarantee hard deadlines

[1] "Transmitting, Fast and Slow: Scheduling Satellite Traffic through Space and Time," ACM MobiCom, 2023

[2] "Collaborative Data Downloading by Using Inter-Satellite Links in LEO Satellite Networks," *IEEE Transactions on Wireless Communications*, 2019

[3] "NB-IoT via LEO Satellites: An Efficient Resource Allocation Strategy for Uplink Data Transmission," *IEEE Internet of Things Journal*, 2022

[4] "Effective Data Collection Via Satellite-Routed Sensor System (SRSS) to Realize Global-Scaled Internet of Things," in *IEEE Sensors Journal*, 2013

[5] "Green Data-Collection From Geo-Distributed IoT Networks Through Low-Earth-Orbit Satellites," *IEEE Transactions on Green Communications and Networking*, 2019

[5] "Edge-Computing-Based Channel Allocation for Deadline-Driven IoT Networks," in *IEEE Transactions on Industrial Informatics*, 2020

[6] "Optimizing Age of Information in Wireless Networks with Throughput Constraints," *IEEE INFOCOM*, 2018

[7] "Age-optimal trajectory planning for UAV-assisted data collection," *IEEE INFOCOM*, 2018

[8] "UAV Trajectory Planning for Data Collection from Time-Constrained IoT Devices," in *IEEE Transactions on Wireless Communications*, 2020

Goal

To efficiently collect IoT data via LEO satellite networks, this work aims to:

1. Schedule IoT data collection with explicitly consideration of
 - Heterogeneous data deadlines
 - Dynamic satellite connections
 - Contention among IoTs for limited resources
2. Objective: maximize the amount of on-time data collection

Outline

System Design

Evaluation

Conclusion

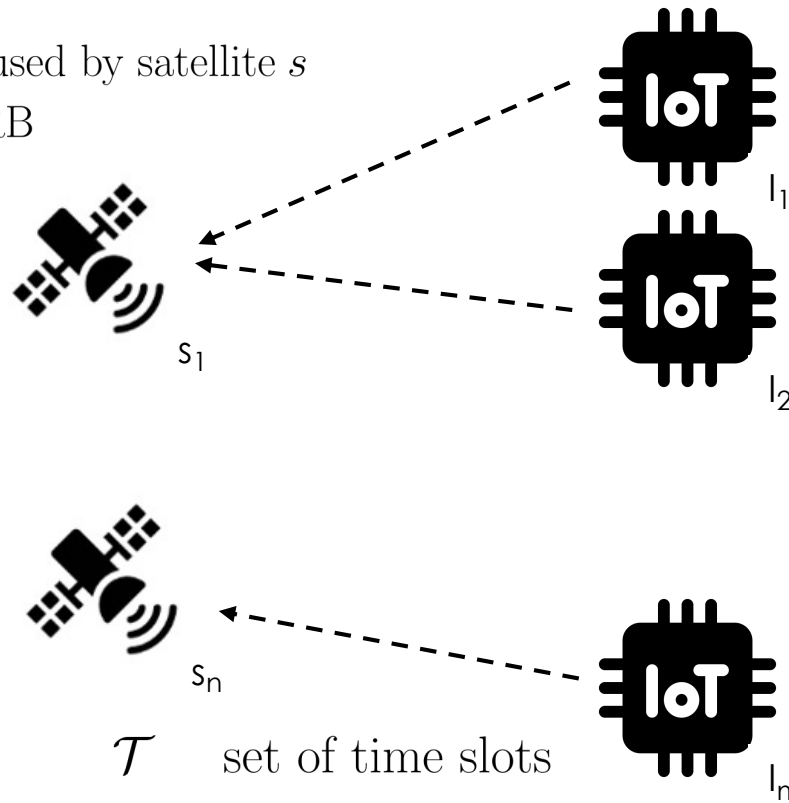
Overview

\mathcal{F}_s set of RBs used by satellite s

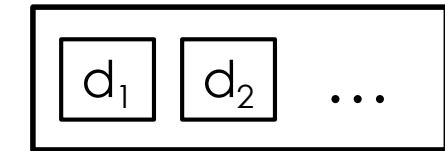
$c_{s,f,t,i}$ rate of an RB

Resource Block

f_{1,t_4}	f_{1,t_3}	f_{1,t_2}	f_{1,t_1}
f_{2,t_4}	f_{2,t_3}	f_{2,t_2}	f_{2,t_1}
f_{3,t_4}	f_{3,t_3}	f_{3,t_2}	f_{3,t_1}



Data



\mathcal{D}_i set of data from IoT i

l_d size of data d

δ_d deadline of data d

\mathcal{T} set of time slots

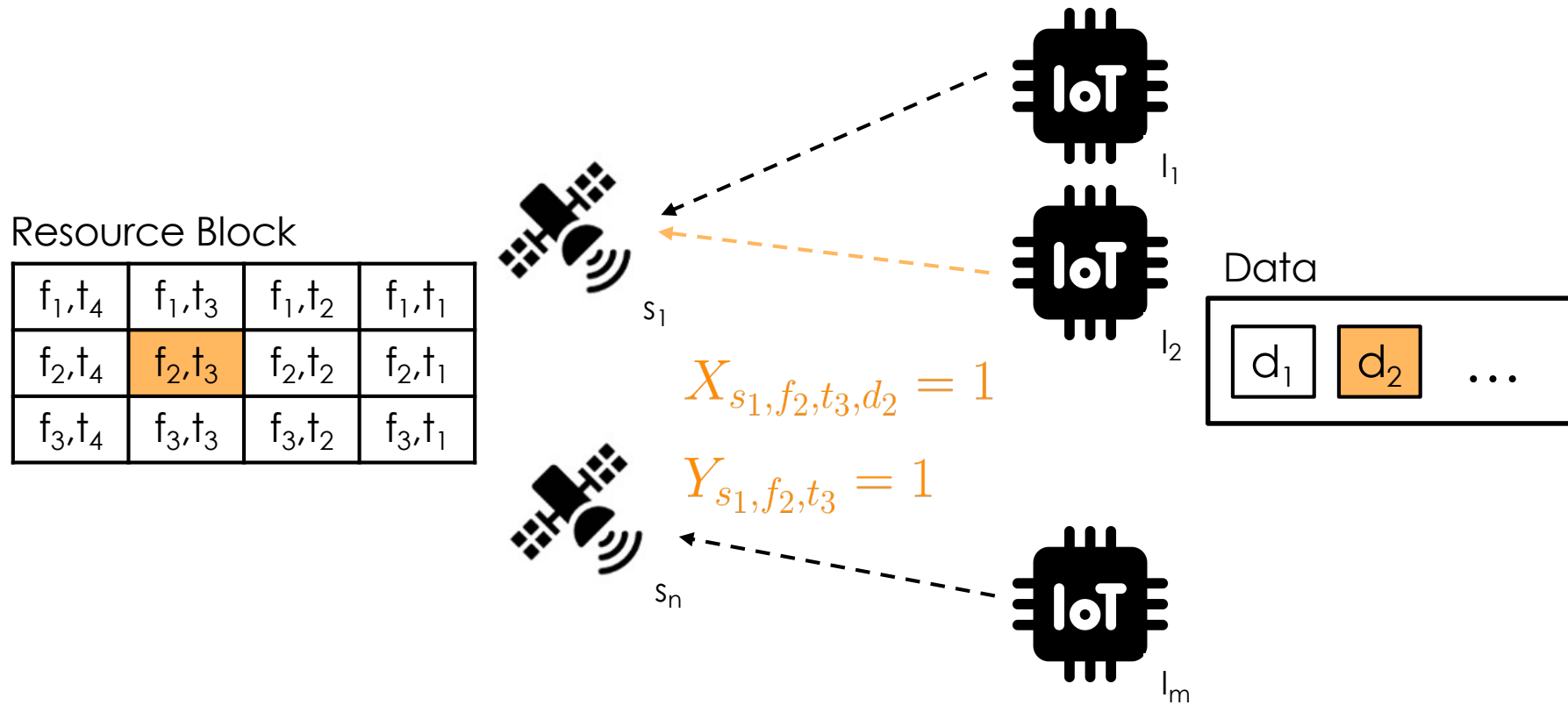
Δt period of time slot

\mathcal{S} set of LEOs

\mathcal{I} set of IoTs

$e_{s,t,i}$ link between s and i

Overview



System Model

Decision Variables:

- whether to allocate RB (f,t) of satellite s to data d of IoT /
 $X_{s,f,t,d} \in \{0, 1\}, \forall s \in \mathcal{S}, f \in \mathcal{F}_s, t \in \mathcal{T}, d \in \mathcal{D}_i$
- whether RB (f,t) of satellite s is occupied
 $Y_{s,f,t} \in \{0, 1\}, \forall s \in \mathcal{S}, f \in \mathcal{F}_s, t \in \mathcal{T}$

Objective: Maximize the total utility function $(v_d - p_d)$

$$\max \sum_{d \in D_i, i \in \mathcal{I}} v_d - p_d$$

- value v_d : amount of data transmitted on time

$$v_d = \sum_{s \in \mathcal{S}} \sum_{f \in \mathcal{F}_s} \sum_{t=1}^{\min(\delta_d, T)} X_{s,f,t,d} * c_{s,f,t,i} * \Delta t, \forall d \in D_i, i \in \mathcal{I}$$

- penalty p_d : amount of expired data

$$p_d = (l_d - v_d) * (\text{sgn}(T - \delta_d) + 1)/2, \forall d \in D_i, i \in \mathcal{I}$$

Constraints

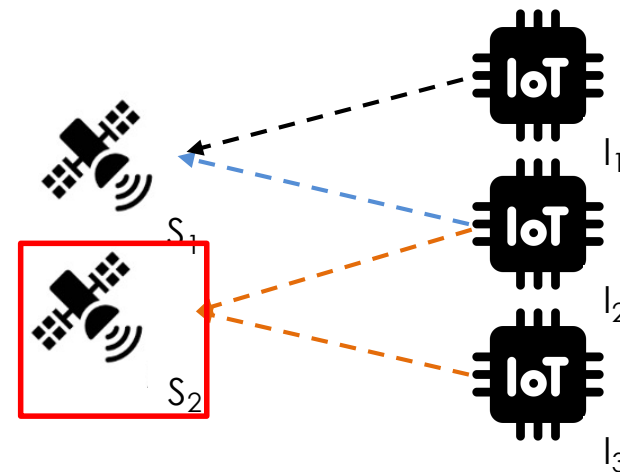
Allocation constraint: one RB allocated to at most one data request

$$\sum_{d \in D_i, i \in \mathcal{I}} X_{s,f,t,d} \leq Y_{s,f,t}, \forall s \in \mathcal{S}, f \in \mathcal{F}_s, t \in \mathcal{T}$$

Interference-free constraint: a scheduled transmission cannot interfere adjacent satellites

$$\sum_{d \in D_i, i \in \mathcal{I}} \sum_{s' \in \mathcal{S}} X_{s',f,t,d} * e_{s,t,i} \leq Y_{s,f,t}, \forall s \in \mathcal{S}, f \in \mathcal{F}_s, t \in \mathcal{T}$$

$$Y_{s,f,t} \leq 1, \forall s \in \mathcal{S}, f \in \mathcal{F}_s, t \in \mathcal{T}$$



Constraints

Data demand constraint: resources allocated to data d should be no more than its demand

$$\sum_{s \in \mathcal{S}} \sum_{f \in \mathcal{F}_s} \sum_{t=1}^{\min(\delta_d, T)} X_{s,f,t,d} * c_{s,f,t,i} * \Delta t \leq l_d, \forall d \in D_i, i \in \mathcal{I}$$

Deadline constraint: avoid allocating RBs to expired data

$$\sum_{s \in \mathcal{S}} \sum_{f \in \mathcal{F}_s} \sum_{\delta_d}^T X_{s,f,t,d} = 0, \forall d \in D_i, i \in \mathcal{I}$$

Problem Formulation

$$\max \sum_{d \in D_i, i \in \mathcal{I}} v_d - p_d$$

$$v_d = \sum_{s \in \mathcal{S}} \sum_{f \in \mathcal{F}_s} \sum_{t=1}^{\min(\delta_d, T)} X_{s,f,t,d} * c_{s,f,t,i} * \Delta t, \forall d \in D_i, i \in \mathcal{I} \quad (\text{value of data})$$

$$p_d = (l_d - v_d) * (\text{sgn}(T - \delta_d) + 1)/2, \forall d \in D_i, i \in \mathcal{I} \quad (\text{penalty of data})$$

subject to

$$\sum_{d \in D_i, i \in \mathcal{I}} X_{s,f,t,d} \leq Y_{s,f,t}, \forall s \in \mathcal{S}, f \in \mathcal{F}_s, t \in \mathcal{T} \quad (\text{Allocation})$$

$$\sum_{d \in D_i, i \in \mathcal{I}} \sum_{s' \in \mathcal{S}} X_{s',f,t,d} * e_{s,t,i} \leq Y_{s,f,t}, \forall s \in \mathcal{S}, f \in \mathcal{F}_s, t \in \mathcal{T} \quad (\text{Interference-free})$$

$$Y_{s,f,t} \leq 1$$

$$\sum_{s \in \mathcal{S}} \sum_{f \in \mathcal{F}_s} \sum_{t=1}^{\min(\delta_d, T)} X_{s,f,t,d} * c_{s,f,t,i} * \Delta t \leq l_d, \forall d \in D_i, i \in \mathcal{I} \quad (\text{Data Demand})$$

$$\sum_{s \in \mathcal{S}} \sum_{f \in \mathcal{F}_s} \sum_{\delta_d}^T X_{s,f,t,d} = 0, \forall d \in D_i, i \in \mathcal{I} \quad (\text{Deadline})$$

Greedy Algorithm

Define a **score** to quantify data importance based on

- Deadline
- Link data rate
- Number of potential interference links

Prioritize data with

- **Urgent** deadline: reduce the penalty
- **Large** link rate: increase upload rate
- **Fewer** interfering links: avoid cross-satellite interference

Greedy Algorithm

Definition of data score for $d \in \mathcal{D}_i, i \in \mathcal{I}$:

$$\omega_d = \alpha_1 \frac{1}{\delta_d} + \alpha_2 \frac{\max_{s \in \mathcal{S}} \sum_{f \in \mathcal{F}_s, t \in \mathcal{T}} c_{s,f,t,i}}{\sum_{s \in \mathcal{S}} e_{s,i}}$$

- **1/deadline**: penalty of deadline
- **rate**: max sum rate supported by a satellite
- **1/number of interference link**: sharing bandwidth with potential interfering links
- α_1, α_2 : weights of the penalty and value

Schedule data in descending order of the scores

Greedy Algorithm

For $t = 1, 2, \dots, T$

Update $e_{s,t,i}, \forall s \in \mathcal{S}, i \in \mathcal{I}$

$$s_i^* = \arg \max_{s \in \mathcal{S}} \sum_{f \in \mathcal{F}_s} c_{s,f,t,i}$$

Update $\omega_d, \forall d \in \mathcal{D}_i, i \in \mathcal{I}$

For $(i^*, d^*) \leftarrow \max_{\delta_d < T, d \in \mathcal{D}_i, i \in \mathcal{I}} \omega_d$

While $(\mathcal{F}_{s_i^*} \neq \phi)$ and $(l_{d^*} > 0)$

$$f^* = \arg \max_{f \in \mathcal{F}_{s_i^*}} c_{s_i^*,f,t,i^*}$$

Update $l_{d^*} \leftarrow l_{d^*} - c_{s_i^*,f^*,t,i^*} * \Delta t$

$\mathcal{F}_s \leftarrow \mathcal{F}_s \setminus \{f^*\}, \forall s \in \mathcal{S}, e_{s,i^*} == 1$

Remove d^* if $l_{d^*} = 0$ or $\mathcal{F}_{s_i^*} = \phi$

For every time slot t

Update connection states

Associate i with the best satellite

Update data scores

Select (i^*, d^*) with max score

Select best RB and allocate

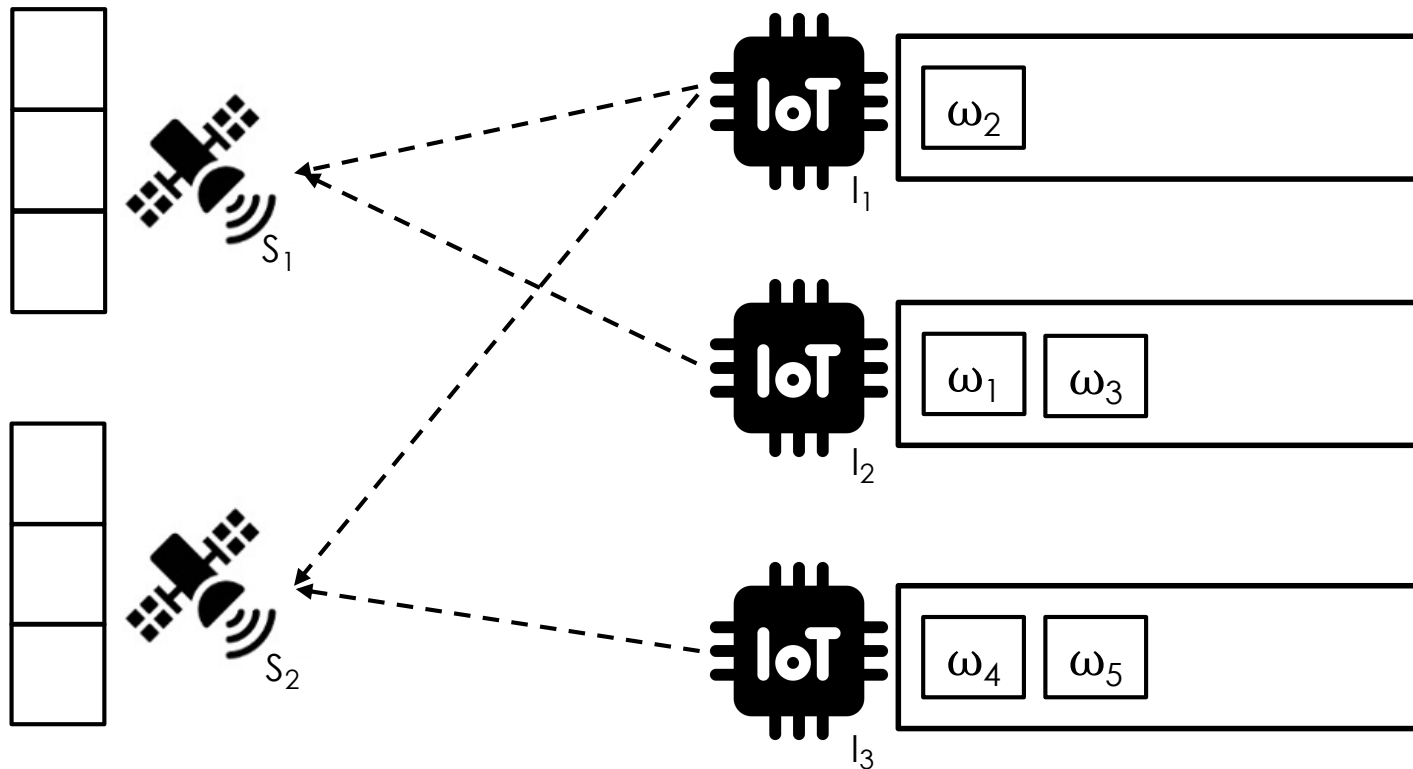
Update residual data demand

Update occupied RB

Removed scheduled data

Example: Scenario

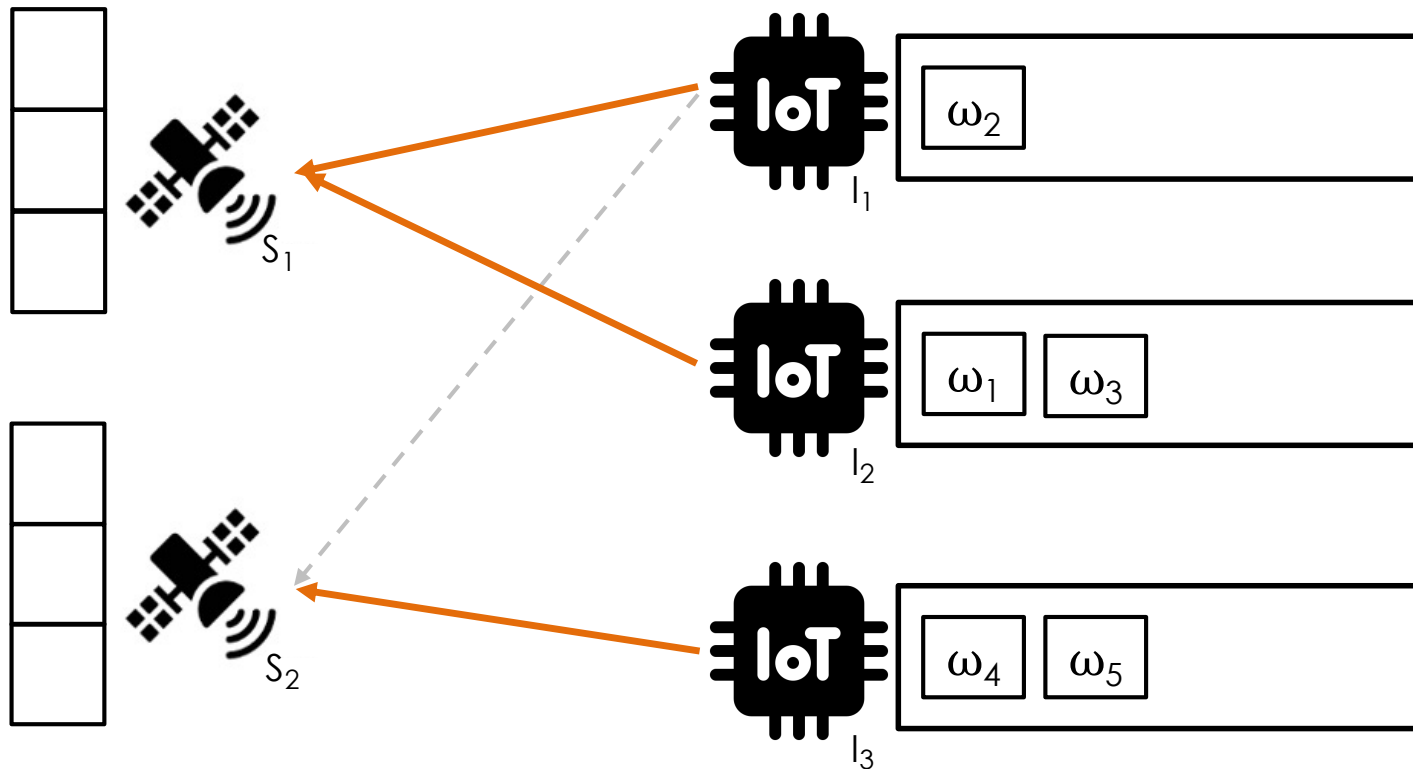
At $t = 0$, 2 satellites and 3 IoTs with 3RBs and 5 data



Example: IoT-LEO Association

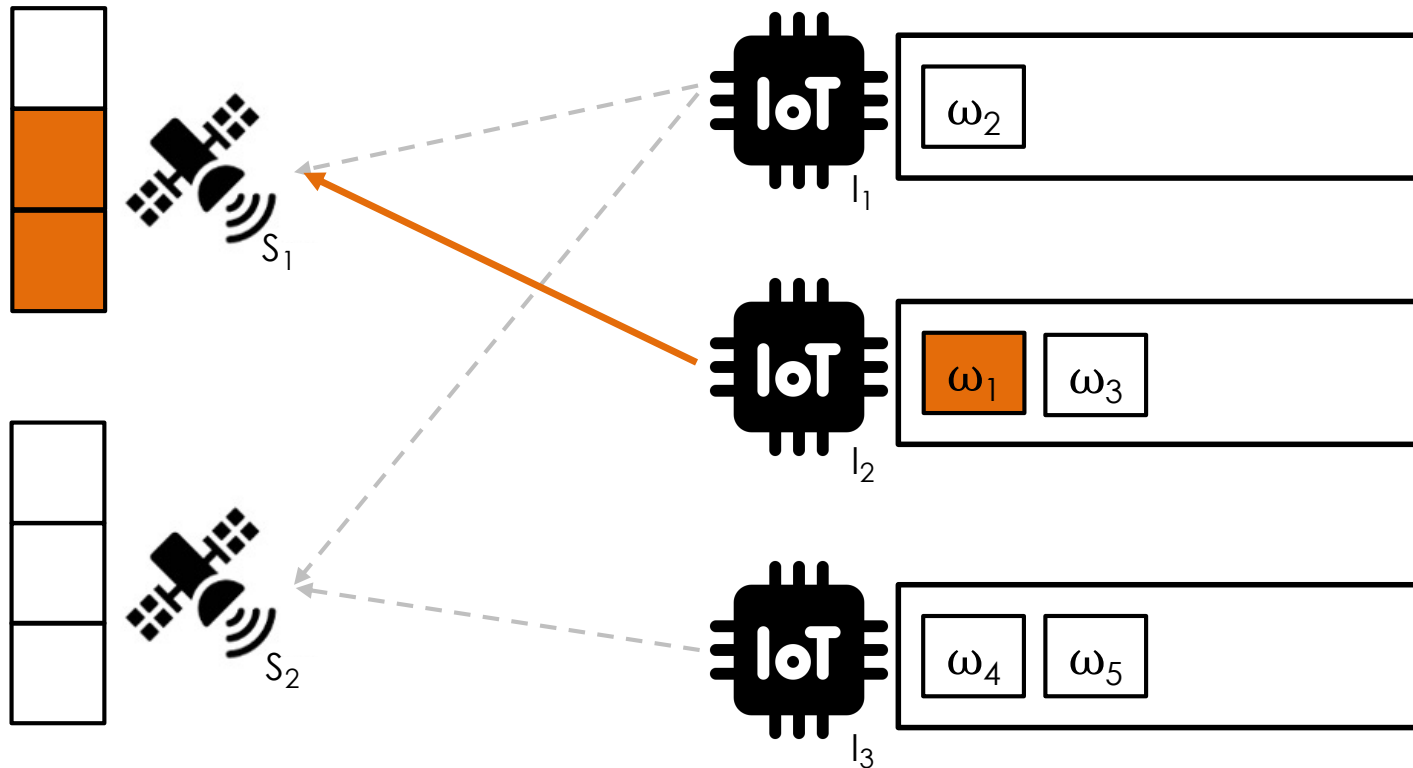
Associate each IoT with its best satellite

Update and sort data scores in descending order



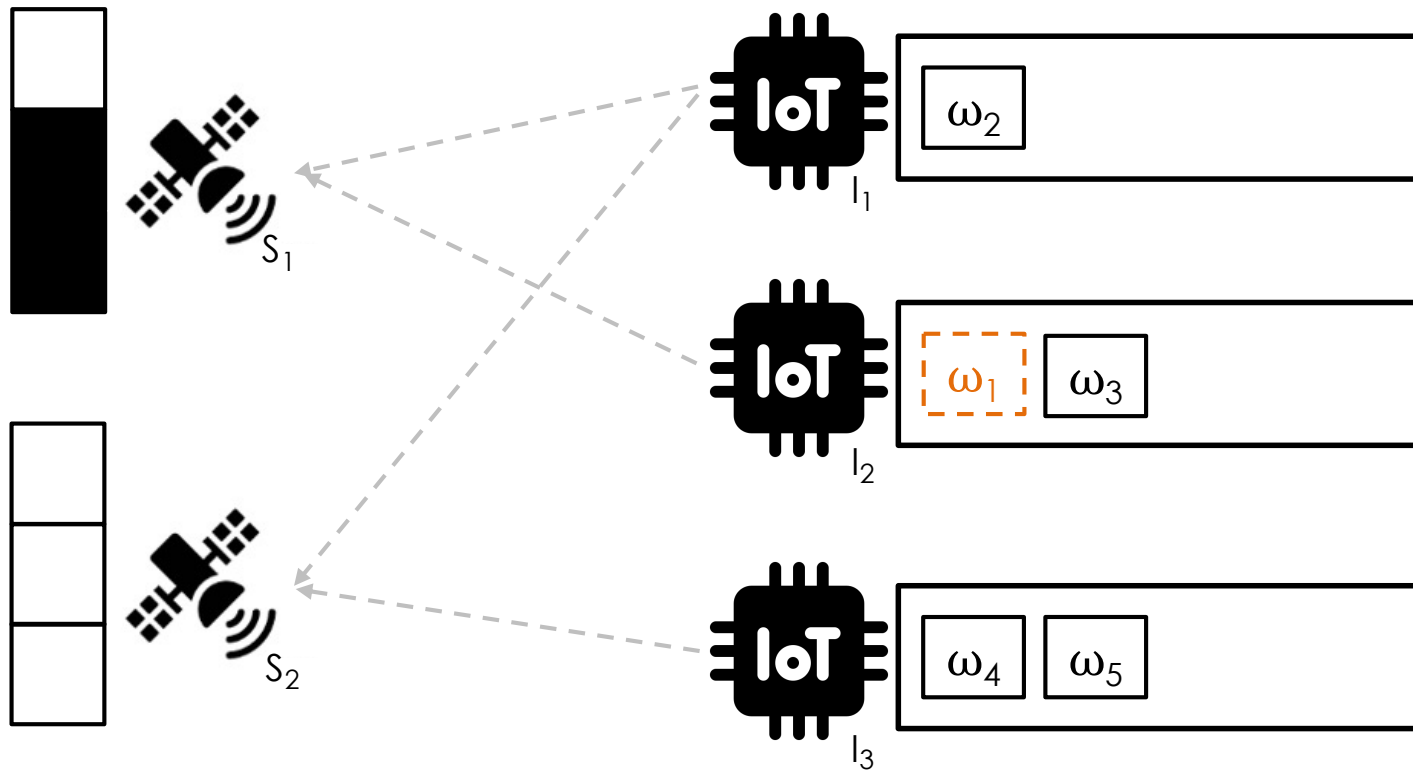
Example: Allocate RBs

Select data d with the highest score
Allocate best RBs for its demand I_d



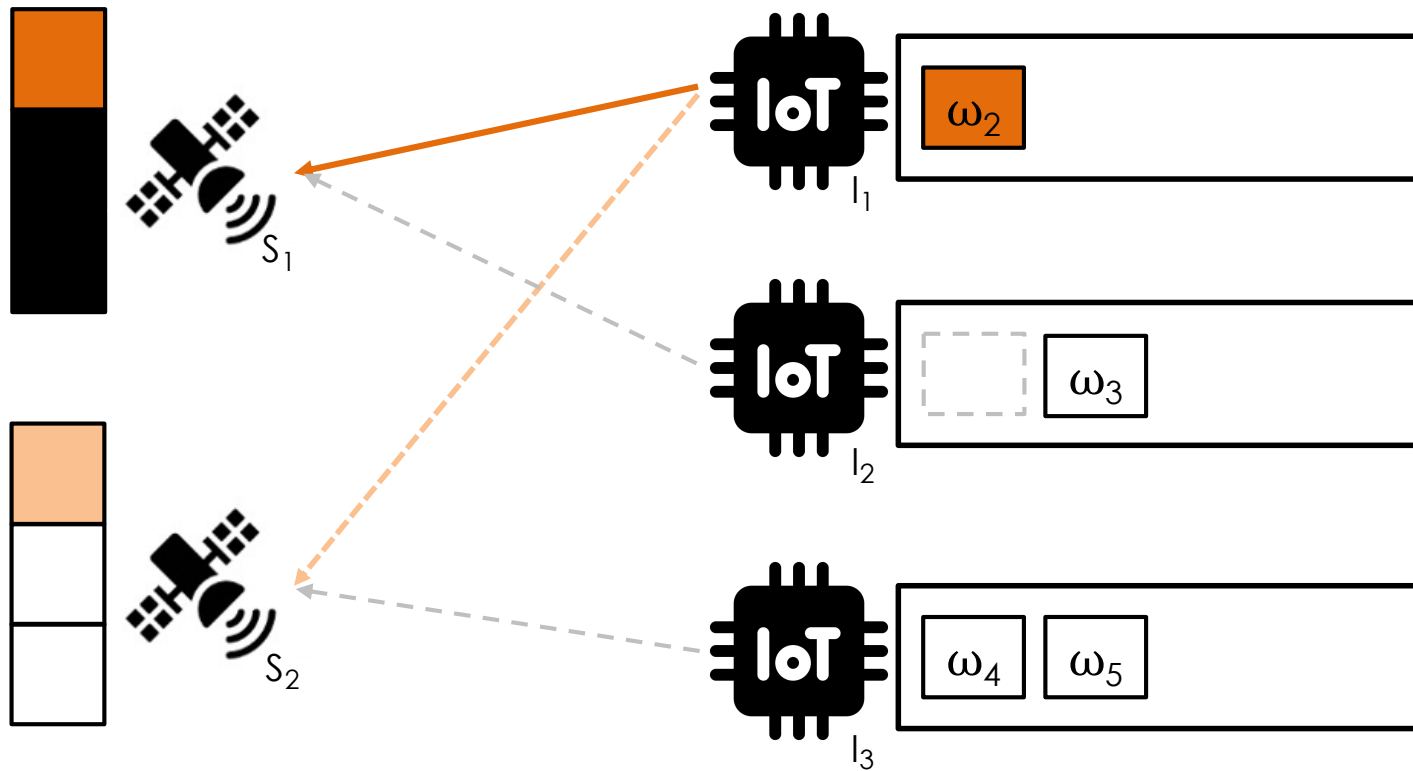
Example: Update Parameters

Remove the data request if $l_d = 0$



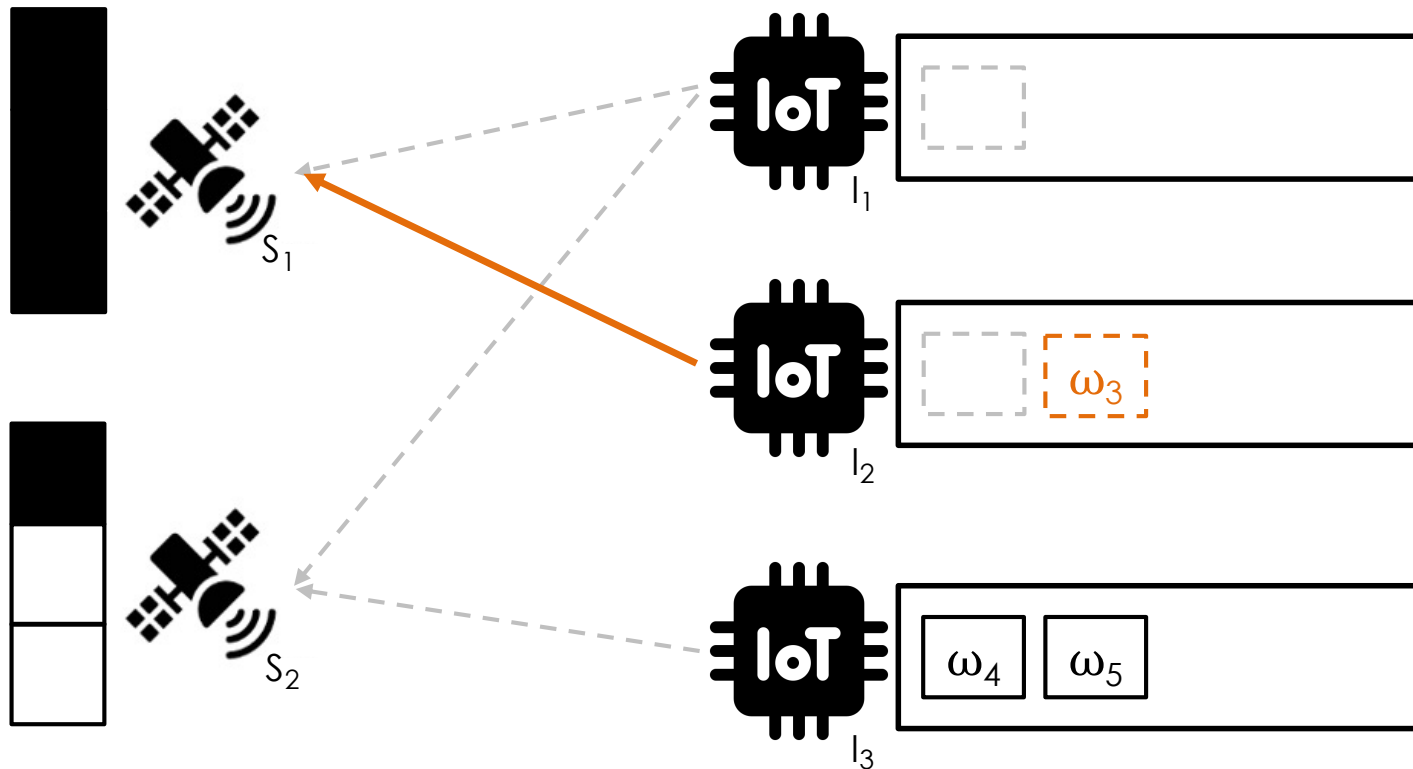
Example: Tag Interfered RBs

Allocate RBs and update interfered RB



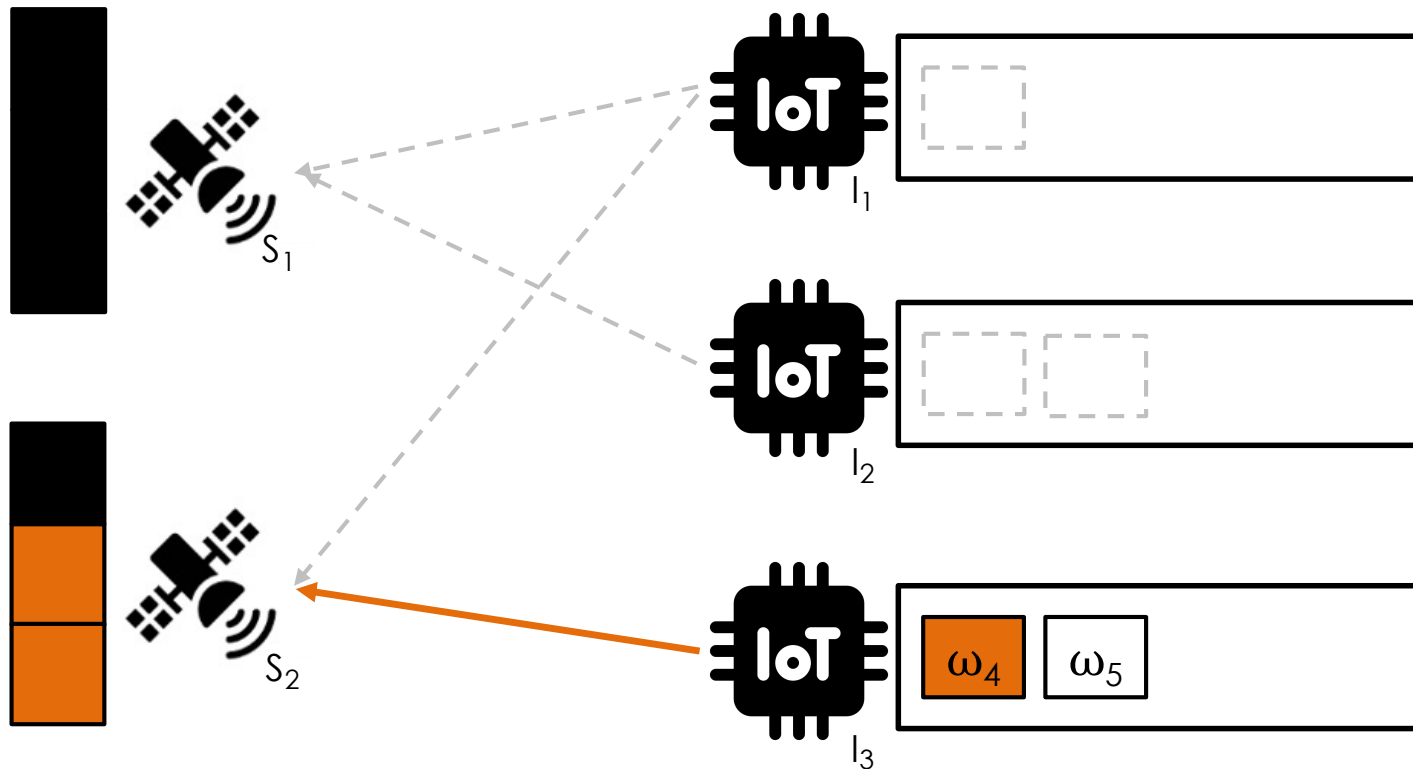
Example: Check Availability

Remove each data request with no available RB



Example: Terminating Condition

Repeat the procedure until no data or RB remains



Outline

System Design

Evaluation

Conclusion

Settings

Duration: $T = 100$ time slots, time slots = 1 ms

Satellite: Globalstar constellation terrestrial band

- Frequency = 2.4 GHz
- Bandwidth = 11.5 MHz

IoT: randomly distributed in a 100×100 km² region

Data:

- Data Size: Pareto Distribution with $P(x) = \frac{\alpha m^\alpha}{x^{\alpha+1}}$
- Data Traffic: 10T(40%), 2T(40%), 1T(15%), and 0.5T(5%)
- Deadline = Zipf distribution $P(x) = \frac{x^{-k}}{\sum_{i=1}^N (1/i^k)}$

Baselines, Metrics and Parameters

Baseline schemes:

- Optimal: Google OR-Tools solver
- Latency-based: schedule with min latency
- Rate-based: schedule with max data rate

Metrics:

- Utility value (value - penalty)
- Percentage of expired data requests

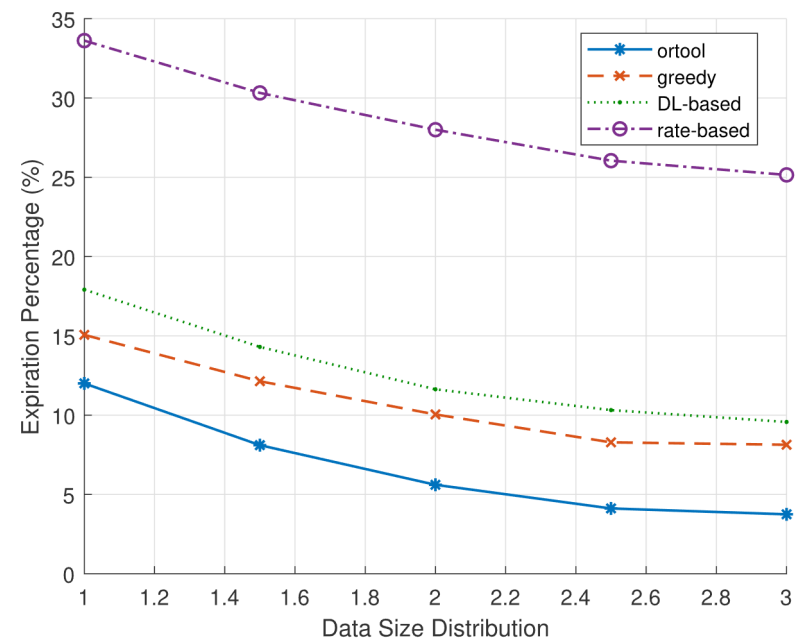
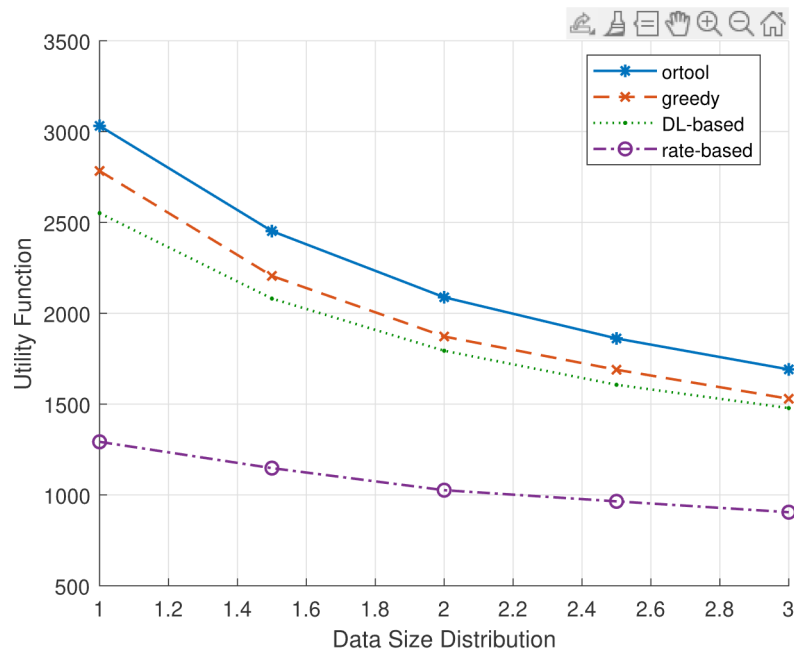
Parameter	Default Value
Data Size Distribution(α)	2.5
Data Size	[20-200] bytes
Deadline Distribution(k)	1
Deadline	[1-T] slots
IoT Number	200
Satellite Number	2
IoT Distribution	random

Impact of Data Size Distribution

Data Size Distribution(α) = [1 1.5 2 2.5 3]

Larger α , Smaller average data size

→ Smaller utility, less expiration

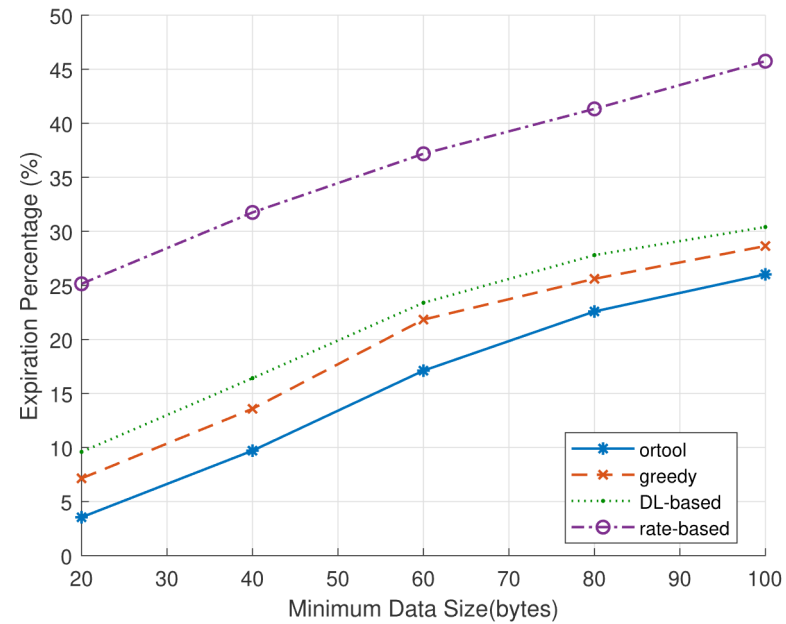
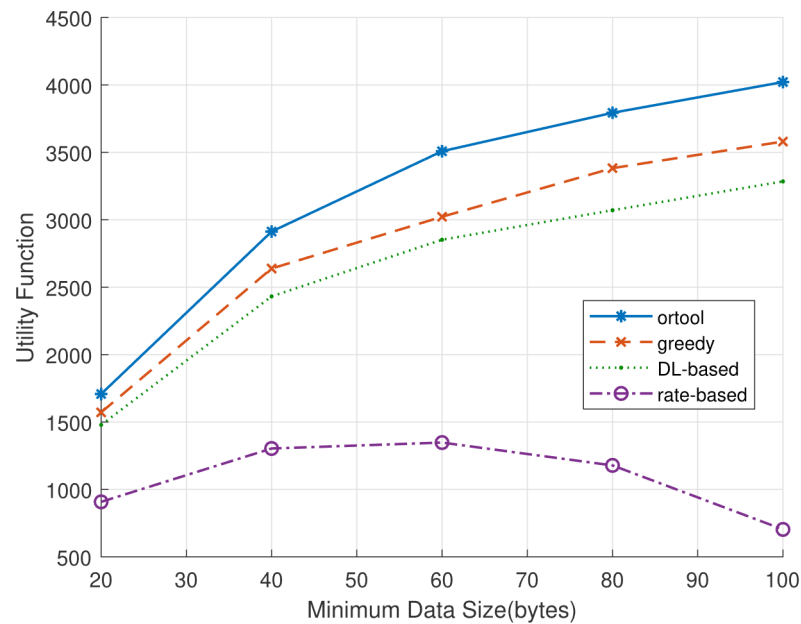


Impact of Minimum Data Size

Minimum Data Size(D_{\min}) = [20 40 60 80 100] bytes

Larger D_{\min} , larger average data size

→ Larger utility, more expiration



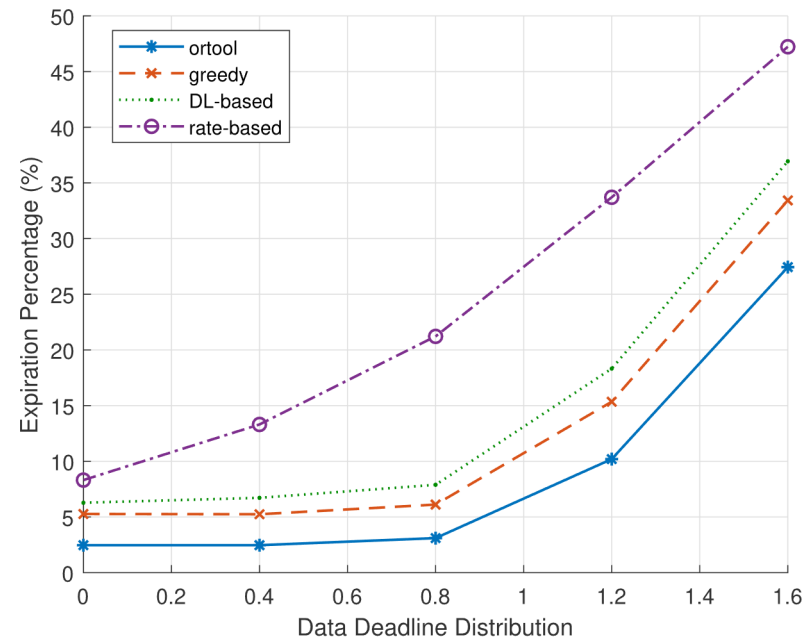
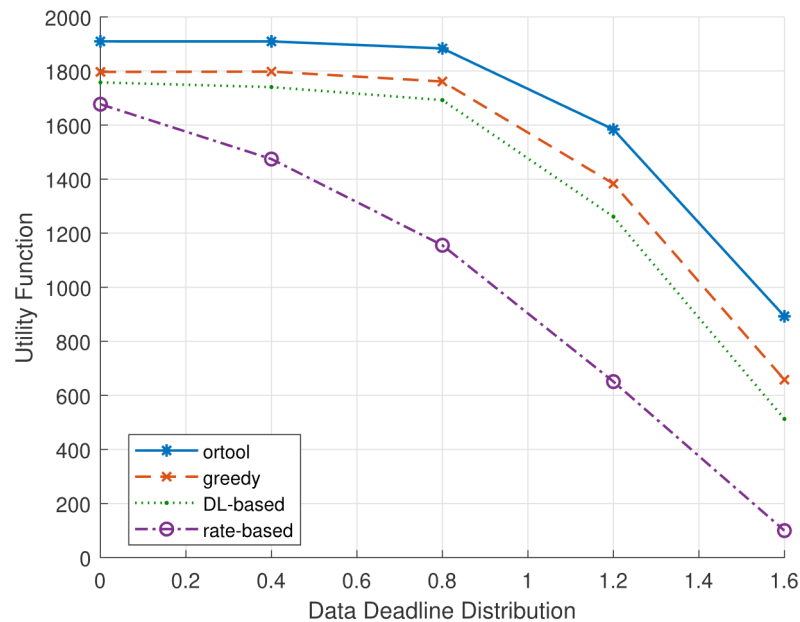
Impact of Deadline Distribution

Deadline Distribution(k) = [0 0.4 0.8 1.2 1.6]

Larger k, smaller average deadline

→ More expiration, smaller utility

→ Gap between greedy & rate-based increases



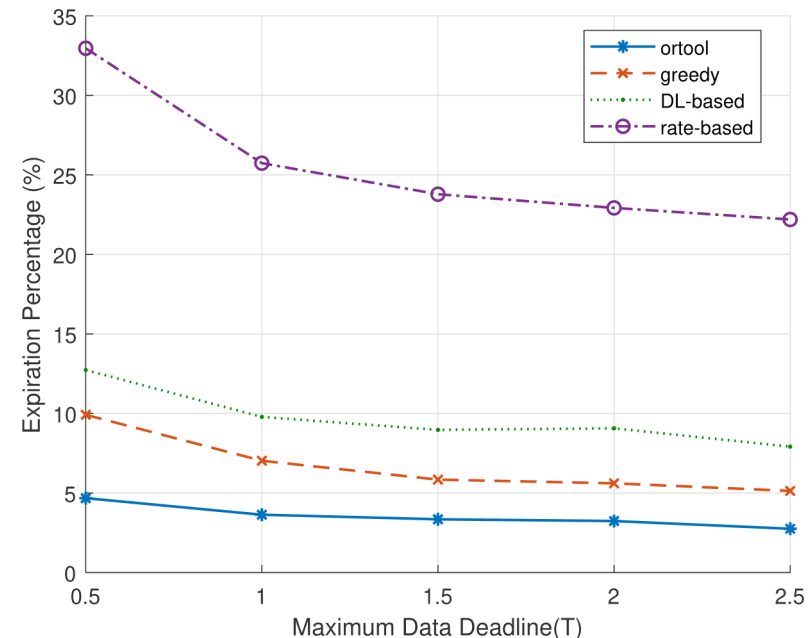
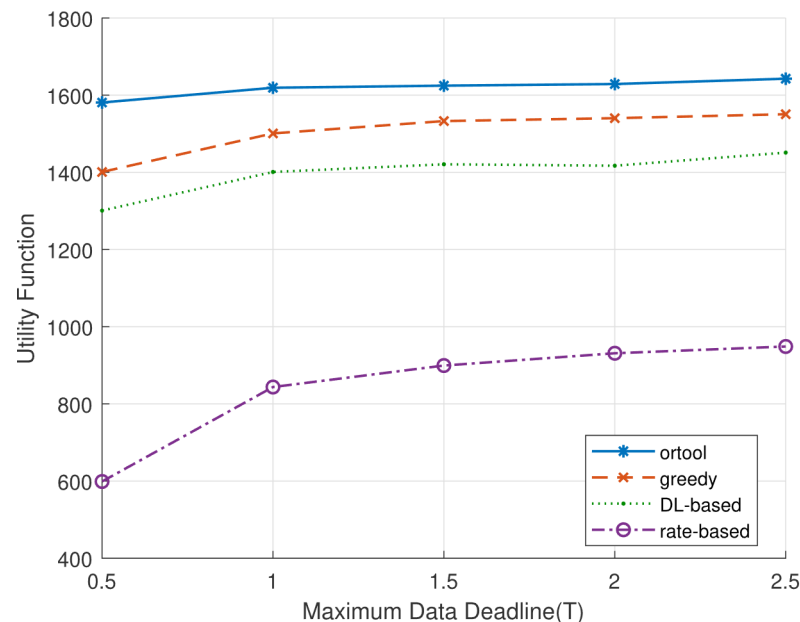
Impact of Maximum Deadline

Maximum Deadline(DL_{max}) = [0.5 1 1.5 2 2.5] T

Larger DL_{max} , larger average deadline

→ Less expiration, larger utility

Greedy is effective with heterogeneous deadlines



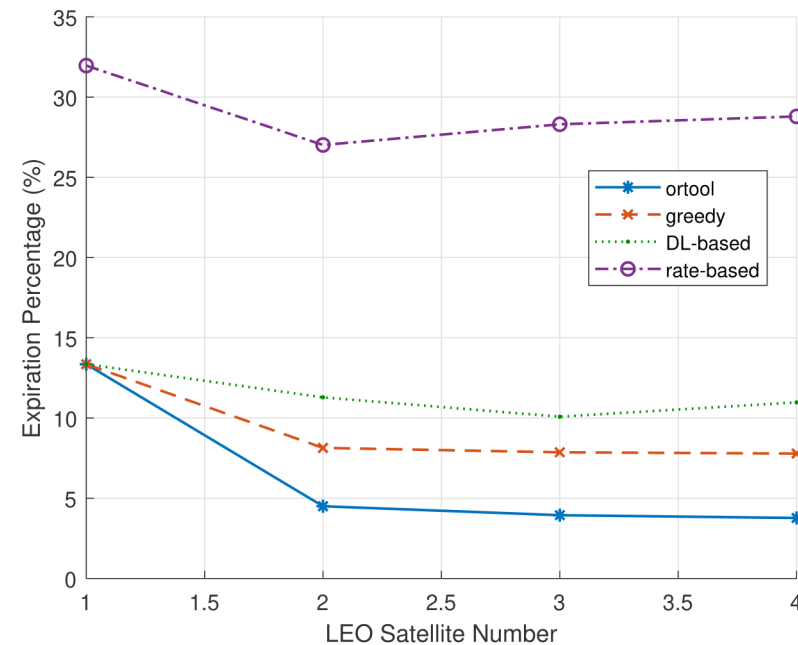
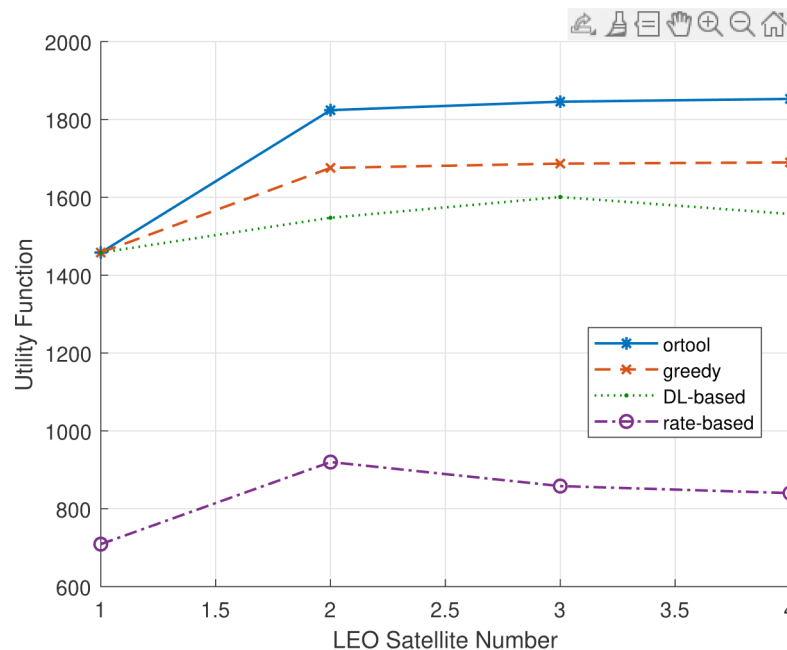
Impact of Satellite Number

Number of satellites (N) = [1 2 3 4]

Larger N, more available resource blocks

→ larger utility, less expiration

→ Effectively consider inter-satellite interference



Conclusion

Schedule data collection based on heterogeneous deadlines of IoT data

Proposed a greedy algorithm to maximize the amount of on-time data collection

Results show the effectiveness of our algorithm under various scenarios